The Prognostic Requirement for Advanced Sensors and Non-Traditional Detection Technologies

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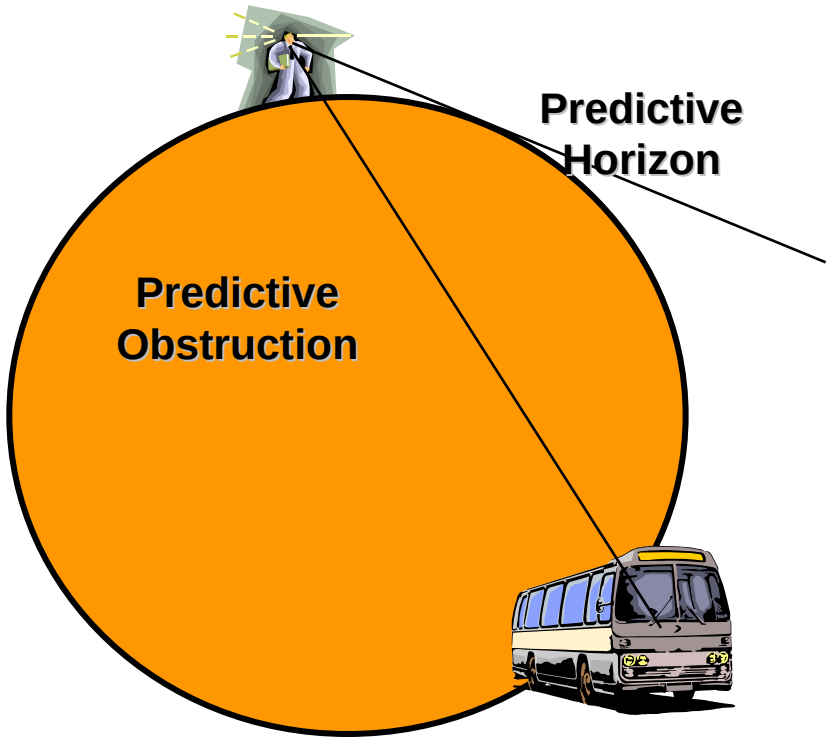
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Prognostic Horizon Level Targets

How Far Do You Want to See Into the Future?

Prognostics: What's Your Perspective?

- Needs and Benefits
- Capabilities: Available and Desired
- Technology "Holes" to be Filled
- Philosophy, Strategy, Implementation
- Integration and Implementation
- Questions:
  - Is It Possible?
  - How are you going to use It?
  - What's Good Enough?



Choose One

- Detect Bus Just Before it Hits You, or
- Detect Bus Far Enough in Advance to Take The "Right" Evasive Action

Current Logistics Structure

High Availability

Ability to Predict Future Health Status

Max Life Usage

MAX SGR

Ability to Anticipate Problems and Req'd Maint Actions

Better FD/FI Efficiency

Quick Turn Around Time

Small Logistics Footprint

No RTOK

Performance Based Maint

Accurate Parts and Life Usage Tracking

Low # of Spares

No False Alarms

Maintenance Mgt

Configuration Tracking

No Surprises

Opportunistic Maintenance

Mission Planning

Short and Responsive Supply Pipeline

No/Limited Secondary Damage

No/Min Inspections

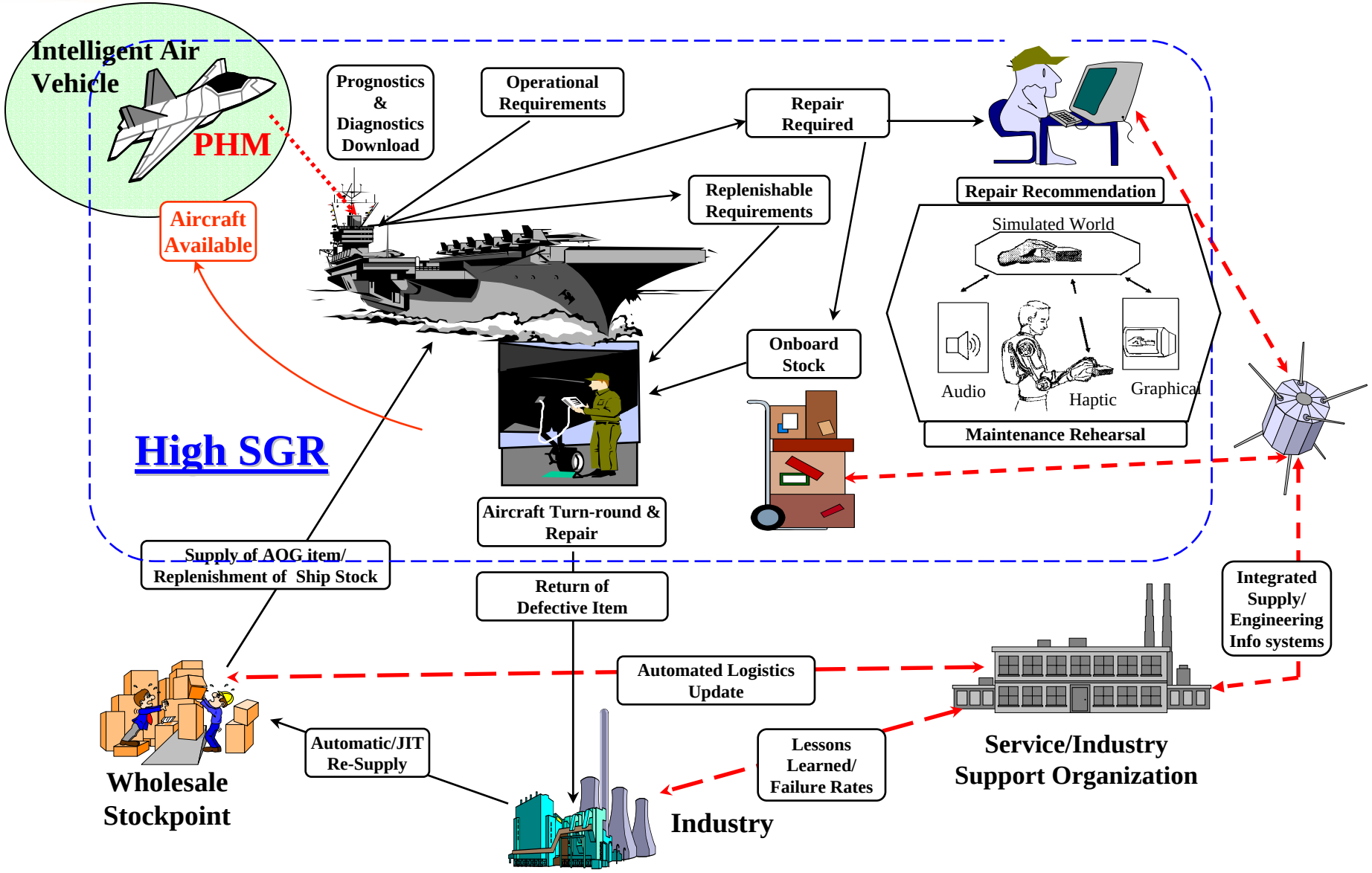
Too Large & Costly

Limit Impact of Quality Control Problems

System Performance Feedback

Immediate Access to all Available Information

Autonomic Logistics Structure



Goals of PHM

- **Enhance Mission Reliability and Aircraft Safety**
- **Reduce Maintenance Manpower, Spares, and Repair Costs**
- **Eliminate Scheduled Inspections**
- **Maximize Lead Time For Maintenance and Parts Procurement**
- **Automatically Isolate Faults to 1 LRC**
- **Eliminate CNDs and RTOKs**
- **Provide Real Time Notification of an Upcoming Maintenance Event at all Levels of the JSF Logistics Chain**
- **Catch Potentially Catastrophic Failures *Before* They Occur**
- **Detect Incipient Faults and Monitor Until Just Prior to Failure**
- **Opportunistic Maintenance Reduces A/C Down Time**

Some Facets of Diagnostics and PHM

- Fault Detection
- Fault Isolation
- Advanced Diagnostics
- Predictive Prognostics
- Useful Life Remaining Predictions
- Component Life Tracking
- Performance Degradation Trending
- Warranty Guarantee Tracking - Enabling New Business Practices
- Selective Fault Reporting
  - Only tells pilot what NEEDS to be known immediately
  - Informs Maintenance of the rest
- Aids in Decision Making & Resource Management
- Fault Accommodation
- Information Fusion and Reasoners
- Information Management
  - Right info to right people at right time

PHM Architecture and Enabling Technologies

Air Vehicle On-Board Health Assessment

ICAWS Manager
Hosted in VMC

Flight Critical

Provides:
- AV-Level Info Management
- Intelligent FI
- Prognostics/Trends
- Auto. Logistics Enabling/Interface

PHM Area Managers

- Propulsion
- VS
- FCS/Utility Subsystems
- Structures
- Signature
- Mission Systems
- MS Subsys

Hosted in ICP

Methods Used:
- Sensor Fusion
- Model-Based Reasoning
- Tailored Algorithms
- Systems Specific Logic / Rules
- Feature Extraction

AVPHM
Hosted in ICP

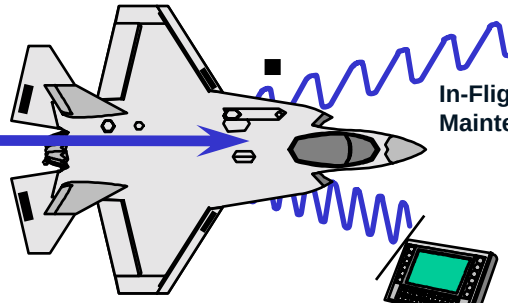
Health Management, Reporting & Recording

NVM — Crash Recorder

PVI — Displays & Controls

Mission Critical

PHM Data — PMD/MM — DTE — PMD



In-Flight & Maintenance Data Link

PMA

PHM / Service Info

Maintenance Panel

MAINTAINER VEHICLE INTERFACE

IETMs
Consumables
On-Board Diagnostics

Autonomic Logistics & Off-Board PHM

Results In:
- Decision Support
- Troubleshooting and Repair
- Condition-Based Maintenance
- Efficient Logistics

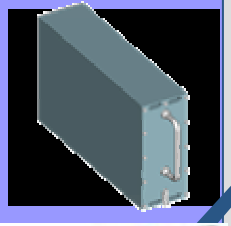
JDIS
- Automated Pilot / Maint. Debrief
- Off-Board Prognostics
- Intelligent Help Environment
- Store / Distribute PHM Information

Database

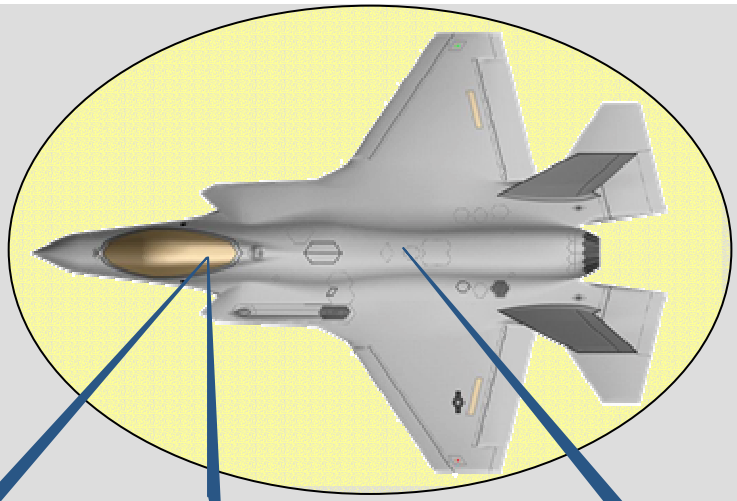
Air Vehicle PHM IPT Products

VS/MS PHM SEIT - Optimal Diagnostic / BIT Capabilities for Subsystem IPT's

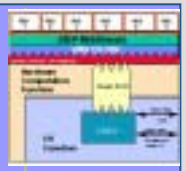





- Diagnostics / BIT Work with the IPT's / supplier teams to achieve the best and most cost effective coverage
- Pertinent data acquisition at sensor, component and sub-system levels.
- Requirements, top level design, use cases, verification.



VS/MS PHM Area Manager (product)



- Enhanced diagnostics, beyond the legacy testability / BIT capabilities, through system models, corroboration, correlation, and information fusion
- Prognosis, collect data, compute life usage

Interface to Off-board PHM (product)

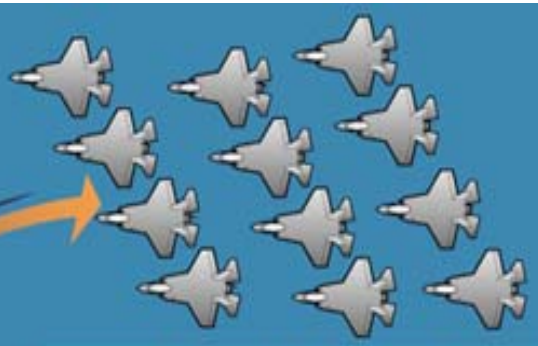
- Prognosis algorithms, estimation of remaining component life
- Failure resolution algorithms

Interface to Air Vehicle PHM (product)

- Health management functional dependencies to be resolved at AV level
- Information broker for on- and off-board users
- High-level service requirements for data reduction, file management

Off-Board PHM Overview

- Downlink Health Data
- Assess and Report Aircraft Health
- Uplink Combat Turn Requirements



Aircraft Support

- Maintainer Vehicle Interface
- Augment Aircraft Diagnostics
- Component Performance Tracking
- Support PHM Maturation

Fleet Support

- Intelligent Help Desk
- Distribute PHM Information
- Support Knowledge Discovery
- Support PHM Maturation

- Report Maint History for Maturation and Sustainment
- Report Usage of Parts/Aircraft
- Distribute Algorithm Updates

- Clear Faults
- Execute Test

- Display Repair Task List
- Execute Diagnostic System Control
- Upload Algorithm Updates

Maintenance Interface Panel

Portable Maintenance Aid

Contractor

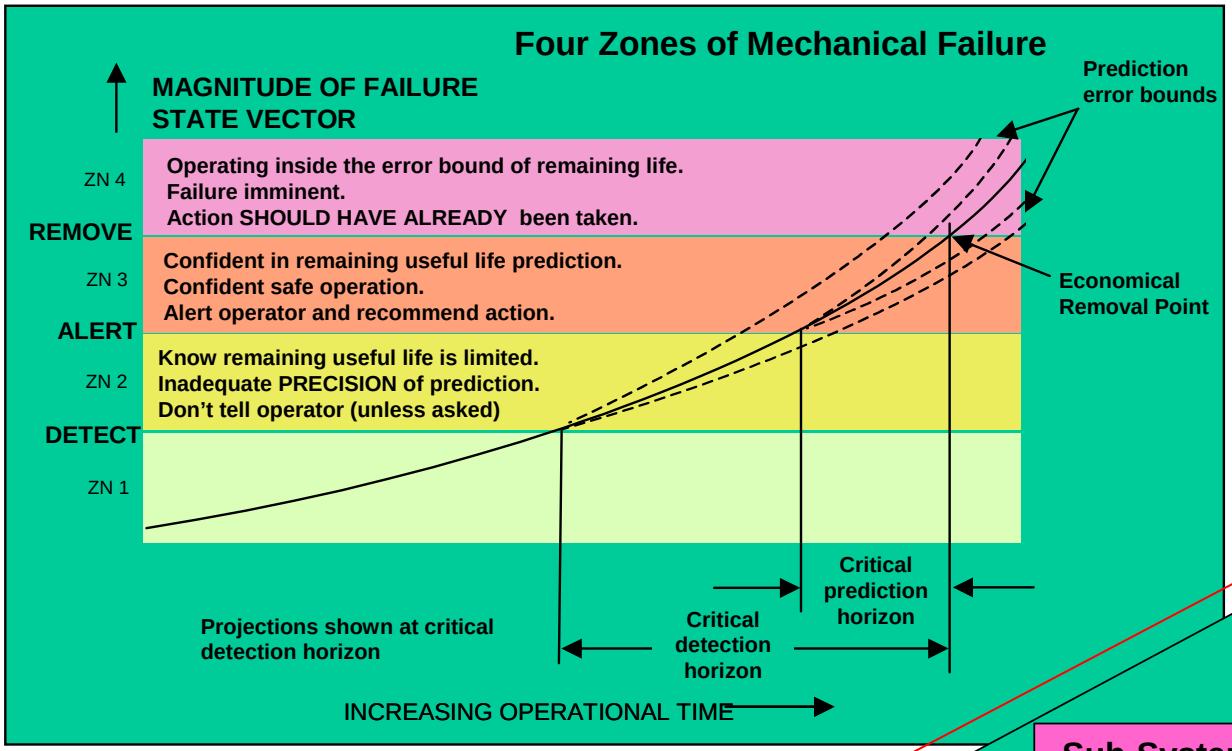
Supplier

J4635006

JSF Subsystem PHM Coverage slide

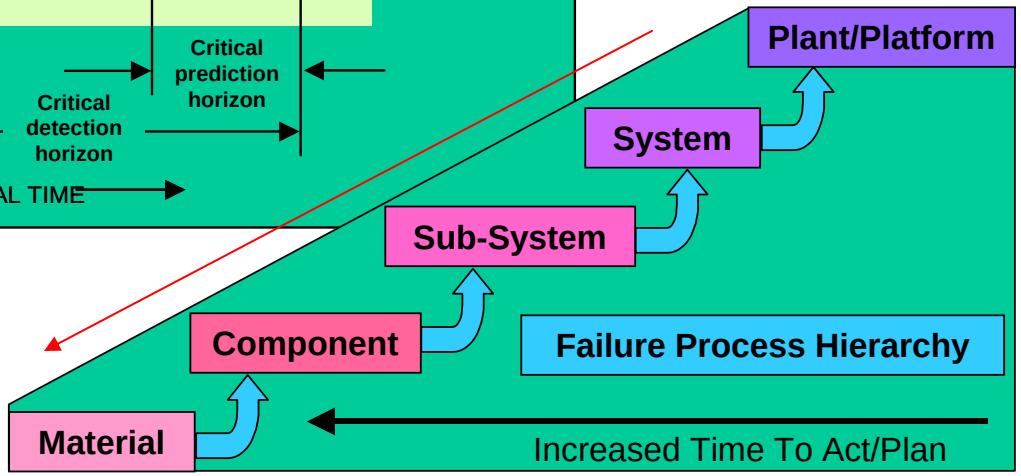
- PHM Requirements including Prognostic “Flowed Down” to All Subsystem Suppliers

Typical Mechanical Failure Progression Questions



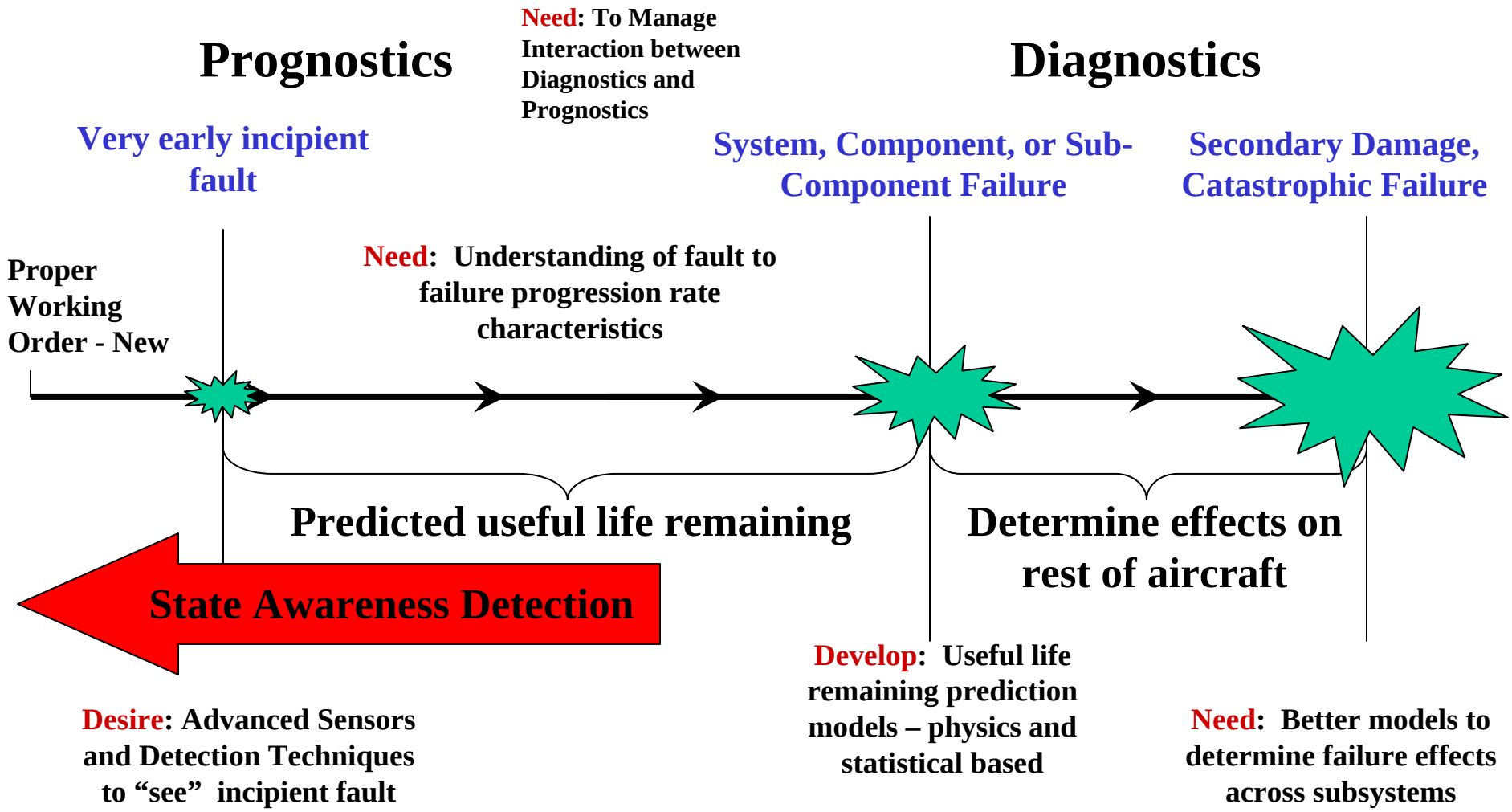
UNDERSTANDING THAT FAILURE IS A PROCESS NOT AN EVENT EMPOWERS A DETECTION PHILOSOPHY WHICH CAN BE EXPLOITED TO MANAGE THE EVENT THAT IS DEVELOPING NOT JUST REACT TO IT.

THE HIGER UP IN THE FAILURE PROCESS HIERARCHY THAT A FAULT IS DETECTED THE LESS MANAGEABILITY REMAINS AND THE LESS TIME EXISTS BEFORE FUNCTIONALITY IS COMPROMISED BEYOND THE USABLE STATE.



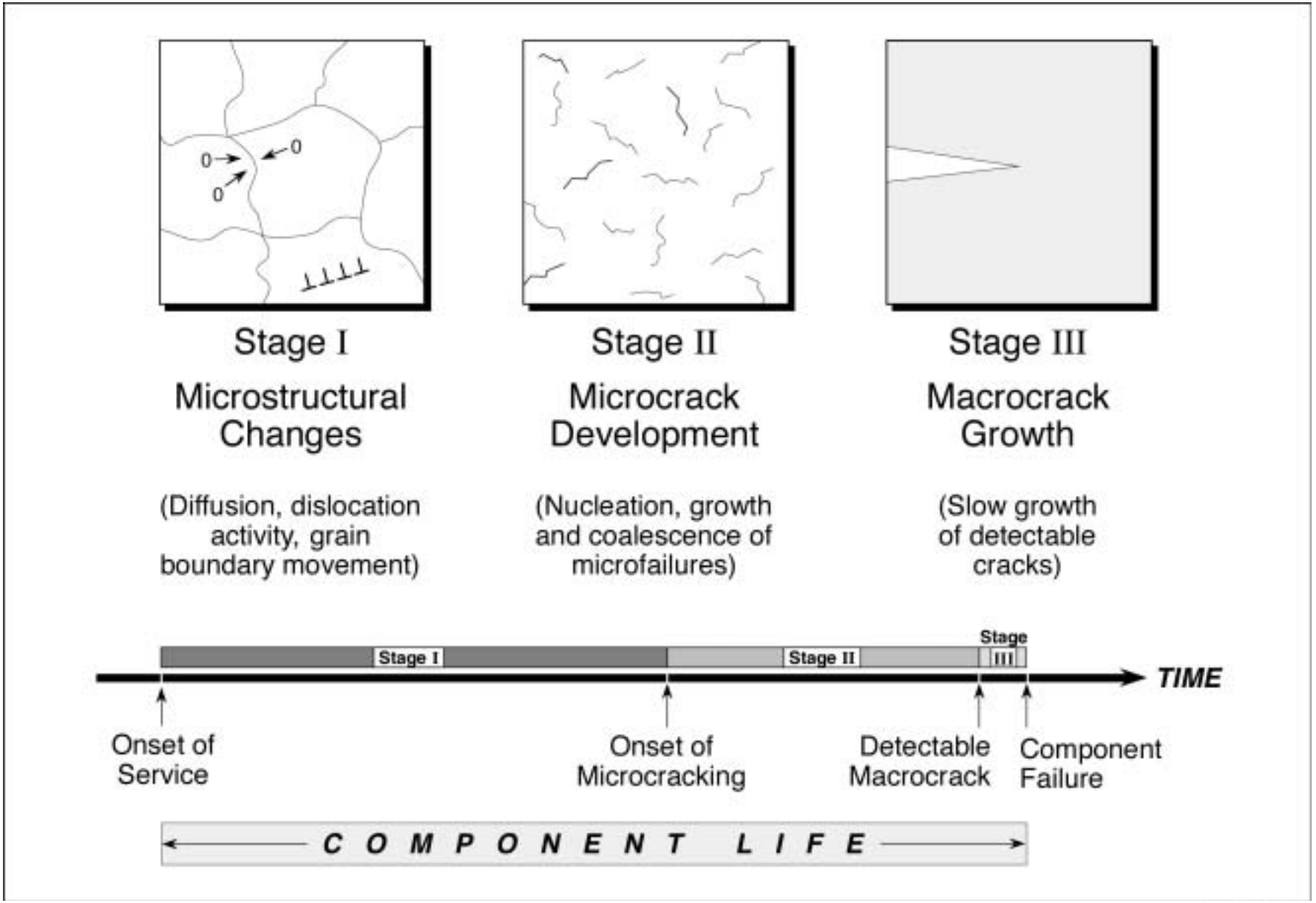
Key to Success is Understanding the Fault Progression Process for Critical Failure Modes. Understanding is best developed by testing.

Failure Progression Timeline



The Goal is To Detect "State Changes" as Far to the Left As Possible

DAMAGE EVOLUTION



Seeded Fault Crack Growth Successfully Detected Using Traditional Vibration Sensor and Advanced Frequency Analysis Techniques

H-60 IGB Pinion Gear Surface Inspection

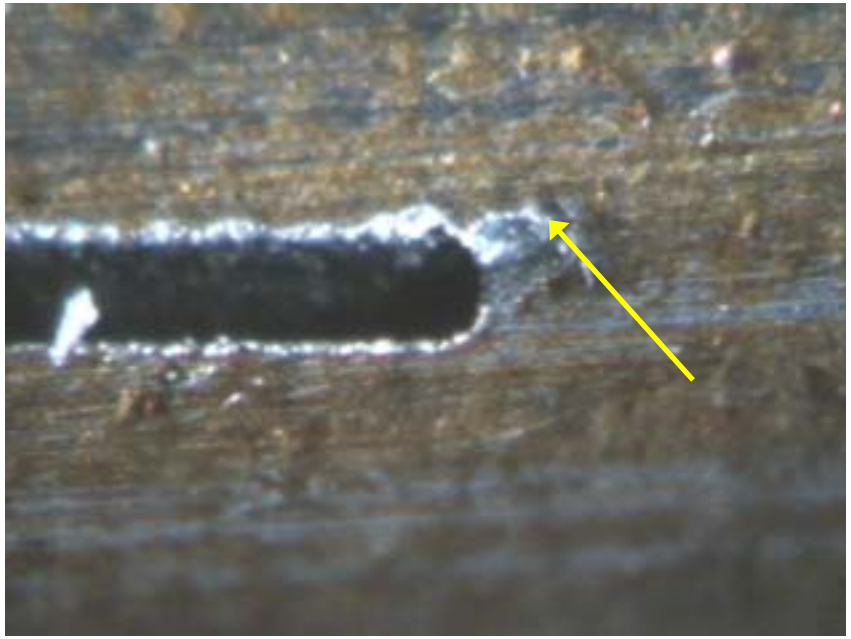
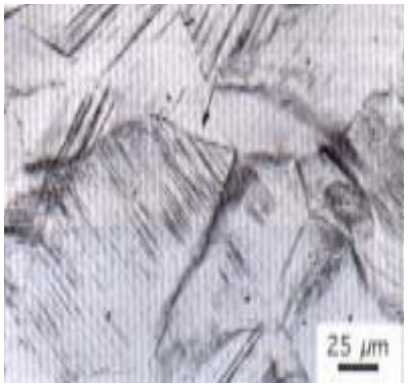


Image of heel notch inner end after Run 15, showing small chip liberated (arrow). No noticeable change until run 18.

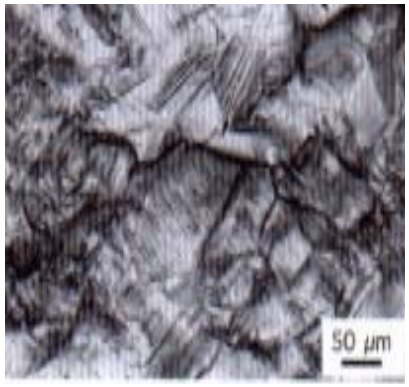
Image of heel notch outer end after Run 18, showing obviously visible crack (arrow).

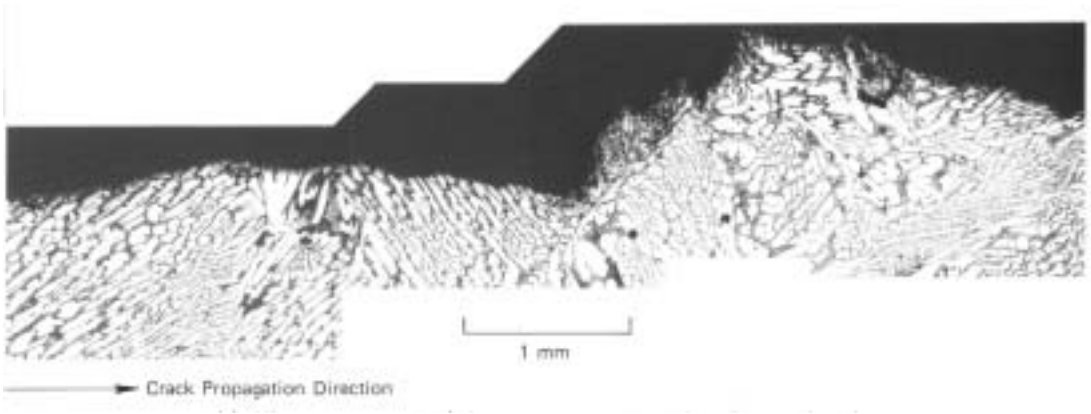
EVOLUTION OF FATIGUE DAMAGE IN NICKEL

After 1200 cycles



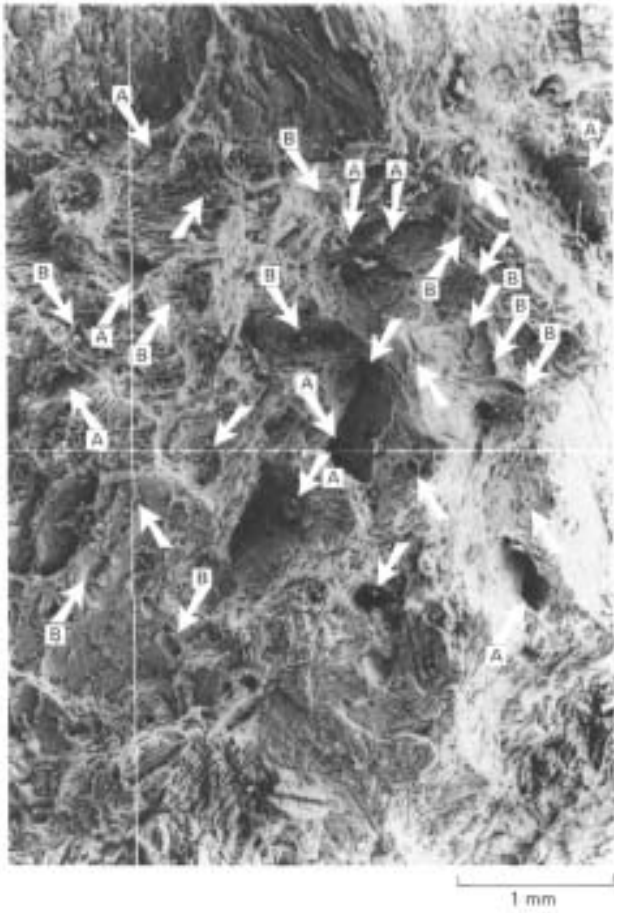
After 4000 cycles





Microstructure damage beneath fracture surface

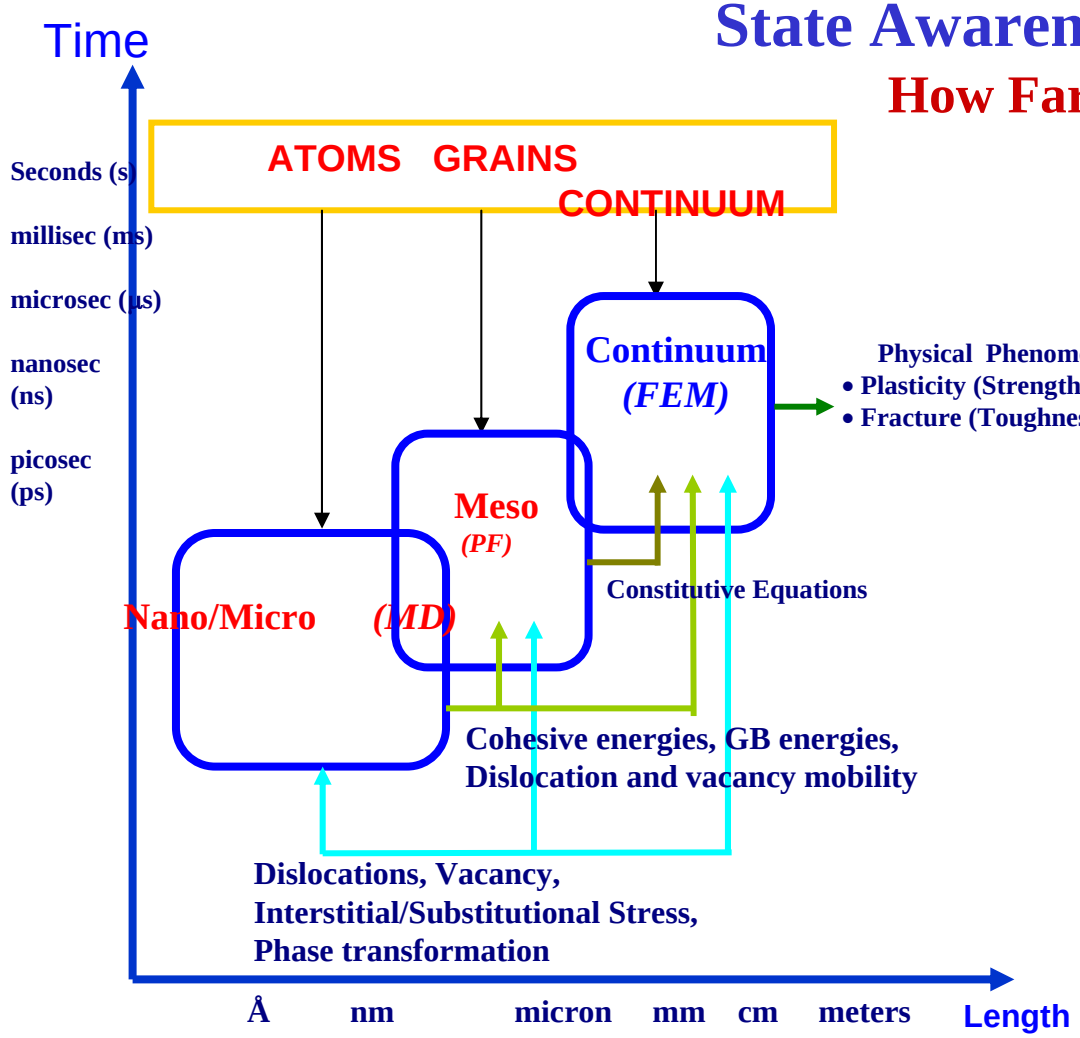
Damage Nucleation Sites in the Microstructure

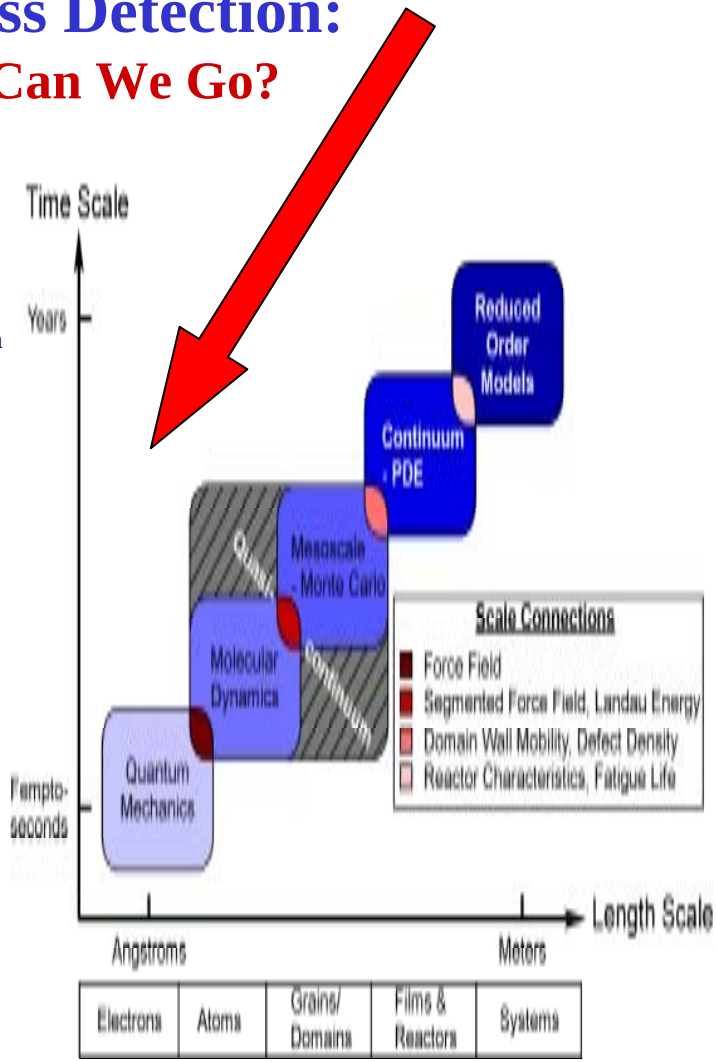


State Awareness Detection – How Far Can We Go ?

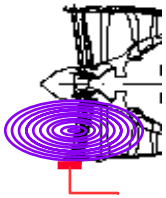
Bridging the Physical Scales

State Awareness Detection:
How Far Can We Go?

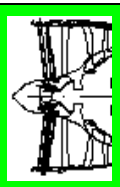




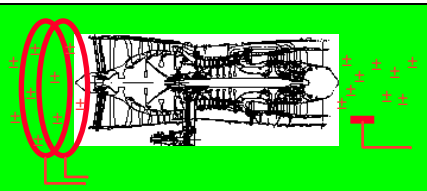
Examples of Some Advanced Sensors and Non-Traditional Detection Techniques



Acoustic FOD Detector (AFD)



Eddy Current Blade Sensor (ECS)
GDATS

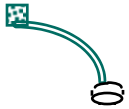


Ingested Debris Monitoring System (IDMS)

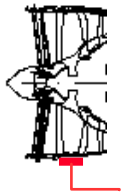
Engine Distress Monitoring System (EDMS)
Smith

Chip Detector

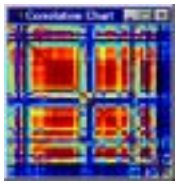
Advanced Vibration



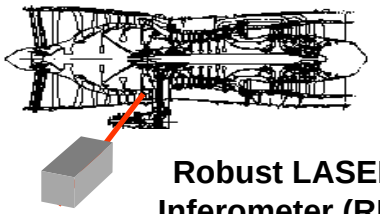
Piezoceramic Patch Crack Detection (PZT)
UTRC



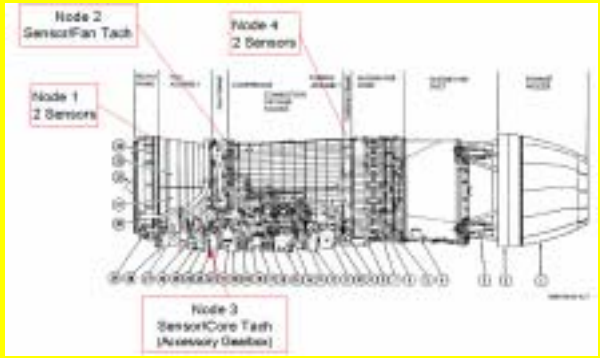
Blade Vibration Meter (BVM8X)
Hood Technology



Beacon-Based Exception Analysis for Maintenance (BEAM) JPL

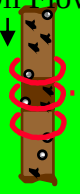


Robust LASER Inferometer (RLI)
Epoch Engineering

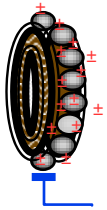


MEMS Sensors

Oil Flow

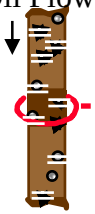


F119 Oil Debris Monitor (ODM)
GasTOPS

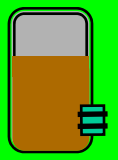


Electrostatic Bearing Monitor (EBM)
Smith

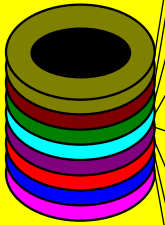
Oil Flow



Electrostatic Oil Debris Monitor (EODM)
ExperTech / SHL

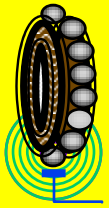


Oil Condition Monitor (OCM)
UDRI



Communications
Diagnostic Processor
General Purpose Processing
Signal Processing
Signal
Power Interface/Generation
Sensing
Self calibration/Active Cancellation

ICHM



Stress Wave Analysis (SWAN)
DME

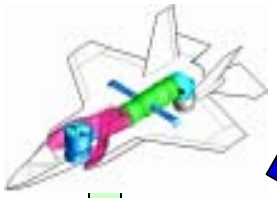
Example Propulsion PHM Elements….Sensors

Sensors are part of the solution

All Sensors are PHM Sensors

...Some also used for control

- **Many Signals**
  - **Most are for Control**
  - **Some PHM Exclusive,**



PHM Exclusive

PHM Exclusive

VMC

FADEC A

FADEC B

PHM

PHM Signal Conditioner (AKA FADEC A)

PHM Signal Conditioner (AKA FADEC B)

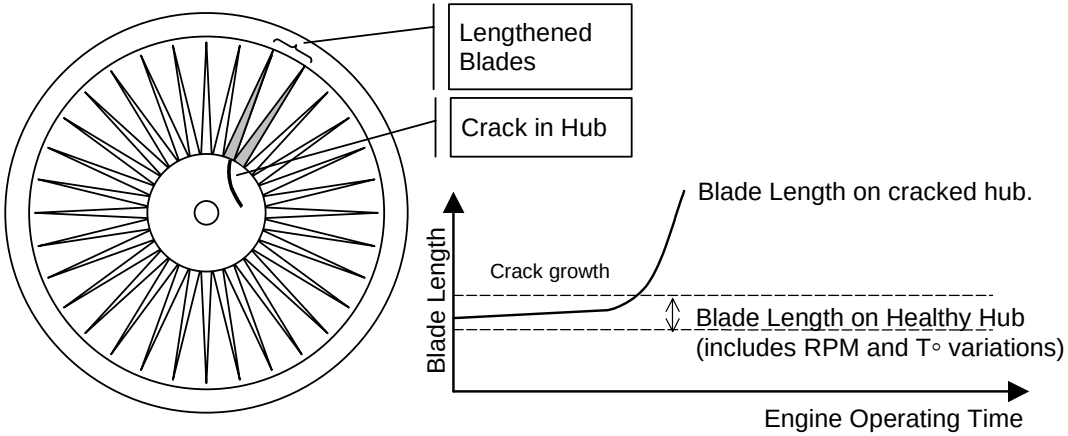
LIFT SYSTEM

ENGINE SYSTEM

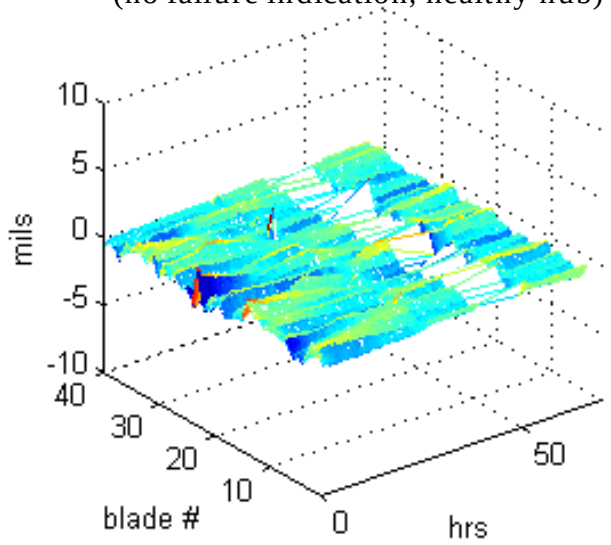
Non-Traditional Detection Technologies

- **Eddy Current Blade Tip Sensors Used for Disk Crack**
- **Electo-Static Exhaust Debris Used for Blade Rub and Turbine “hot end” Degradation**
- **Electro-Static Wear Site Detector for Bearing Degradation**
- **Very High Frequency Vibration Analysis, +1000 KHz**
- **Apply Laboratory and Test Instrumentation, Bench Inspection and NDT Techniques in Innovated Ways**
- **New and Aggressive Use of MEMS Technologies**
- **Advanced, Sophisticated, and Innovated Data Analysis**
  - **Applied from Other Disciplines**

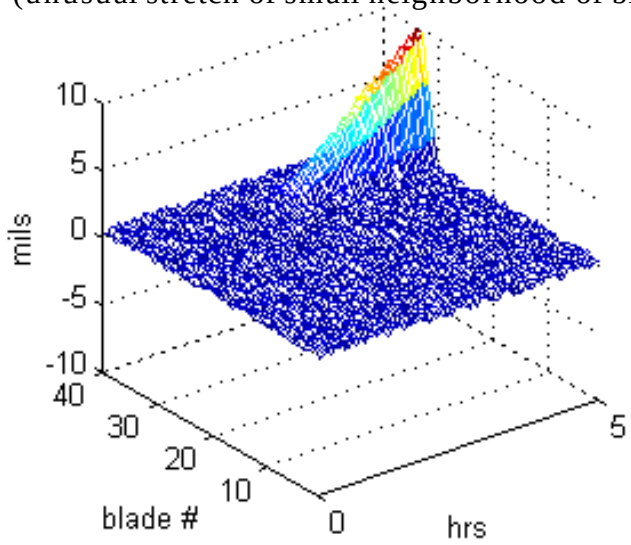
Non-Traditional Detection Technologies
Disk Integrity – Crack Detection



Measured Unusual Blade Stretch
(no failure indication; healthy hub)



Simulated Anticipated Hub Burst Failure Signature
(unusual stretch of small neighborhood of blades)



Blade clearance compensated for temperature and imbalance has been measured to within +/- .001".

Smart Sensing Technologies

- **Smart Sensors**
  - **-Very Small, Wireless, Much Processing Power**
  - **- MEMS based**
- **Smart Materials**
  - **- Skins, Coatings, Layered, etc**
  - **- Part of Design and Manufacturing Process**
- **Embedded Sensors**
  - **- Integral with Material and/or Design**
- **Embedded Detectable Materials**
  - **- Enable Easier and/or Earlier Detection**
  - **- Make Traditional Sensors More Capable**
  - **- Make Detection Techniques More Sensitive**

Notional Strategy and Template for Prognostics

- **Identify and Target Components and Sub-Elements Suitable for Prognostics**
  - **Those with understandable fault to failure progression characteristics**
  - **Those that are Important to do: Safety/Mission Critical, High Value, etc.**
  - **Eliminate those impossible or too hard to consider**

- **Use and/or Develop Suitable Detection Techniques and Technologies**
  - **Sensor and Parameter Based**
  - **Very Data Analysis Driven**
  - **Used Advanced and Non-Traditional Approaches**
  - **Take Advantage of Information ("Hear and Usage") at the Material Level**
- **Develop and/or Obtain Advanced Integrated Models**
  - **Understand the Physics of Failure, Component Design, and Materials Properties**
  - **Fault to failure progression characteristics**
  - **Useful life remaining**
  - **Physics Based, Statistical Based, Detector Driven, Usage Based**

- **Perform Experimental Seeded Fault Tests**
  - **As many as affordable**
  - **Designed for Specifically the Development of Prognostic Capabilities**
- **Verify and Validate Models**
  - **Blind Testing**
  - **Modeling and Simulation**
- **Modify Useful Life Remaining Prediction Model to Account for Real World Considerations**
  - **Power Driven Parameter Profiles**
  - **Actual Mission Usage Profiles**
  - **CONOPS**
- **Integrate Capabilities with System Architectures and Logistics Concepts**

Detection, Isolation &Prognosis

Detection

Through sensors, Models etc

Isolation

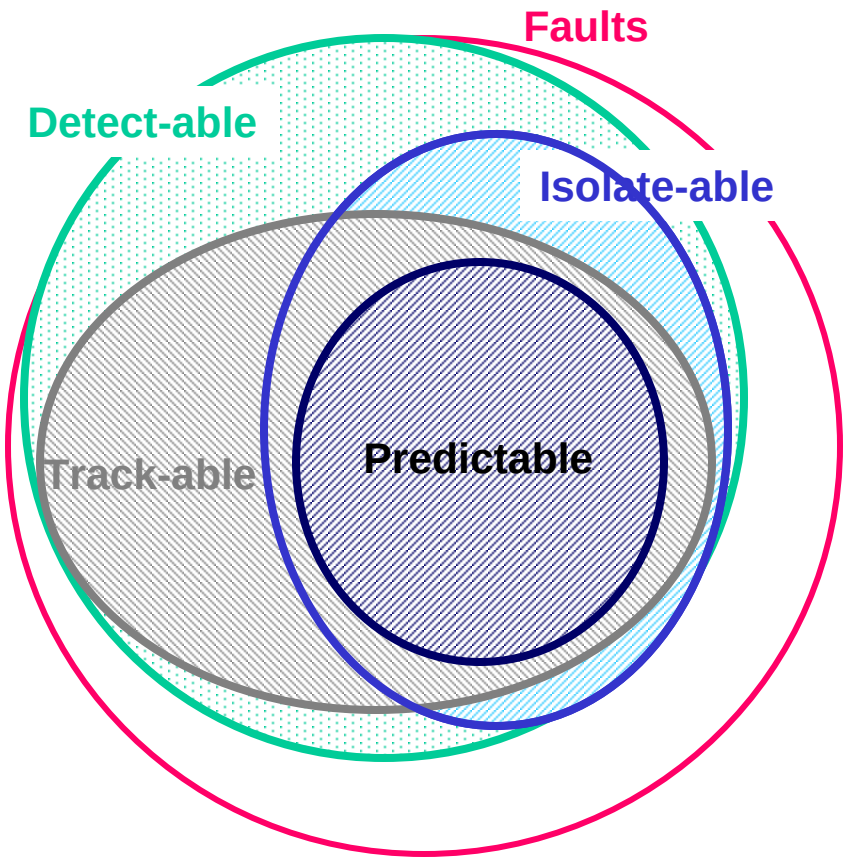
Information fusion from sensors, Models etc.

Tracking/Trending

Processed PHM data

Prediction/Prognosis

Based on tracking/trending, and lifing models

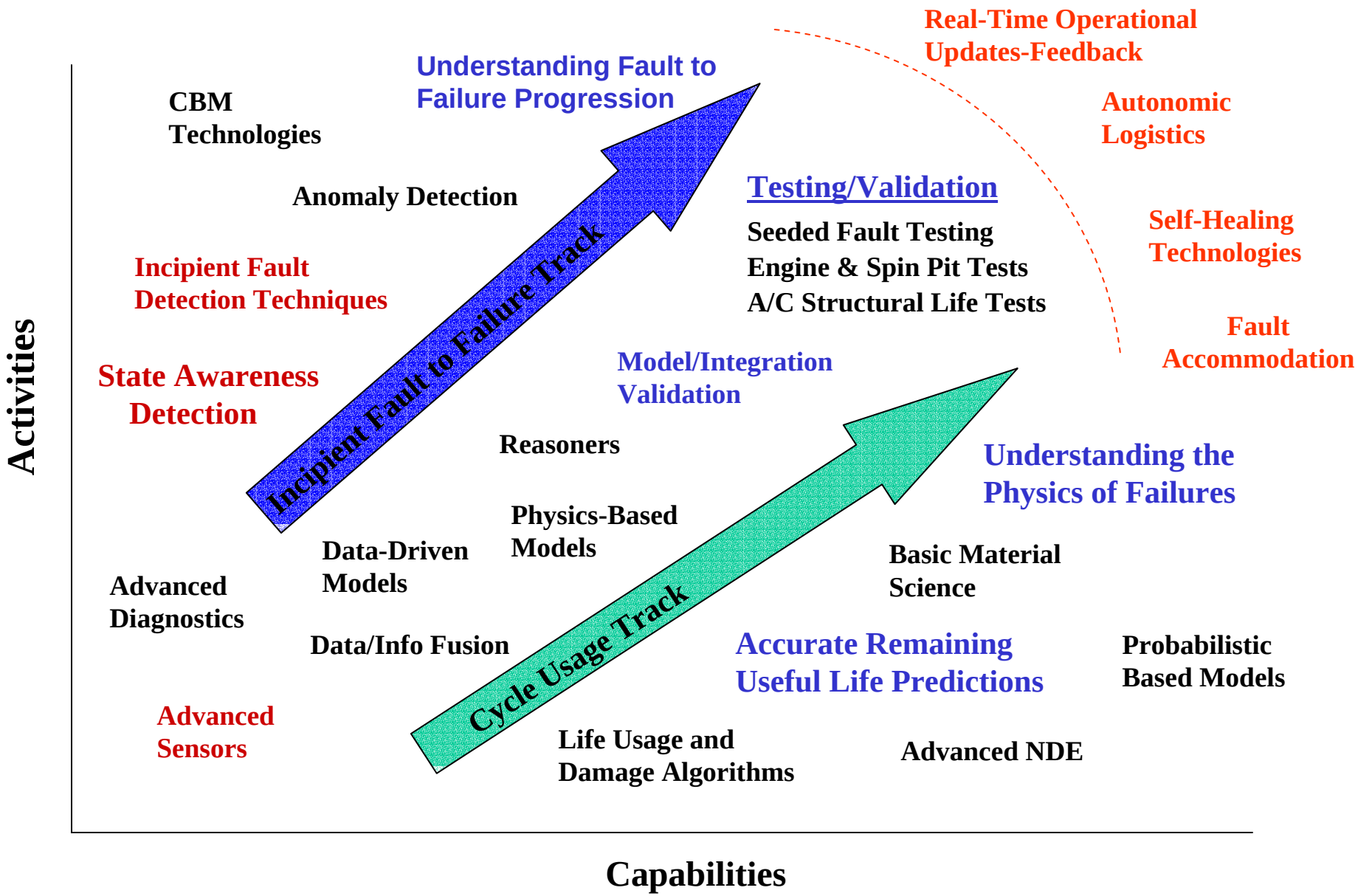


Prognostics: What We Are Missing ?

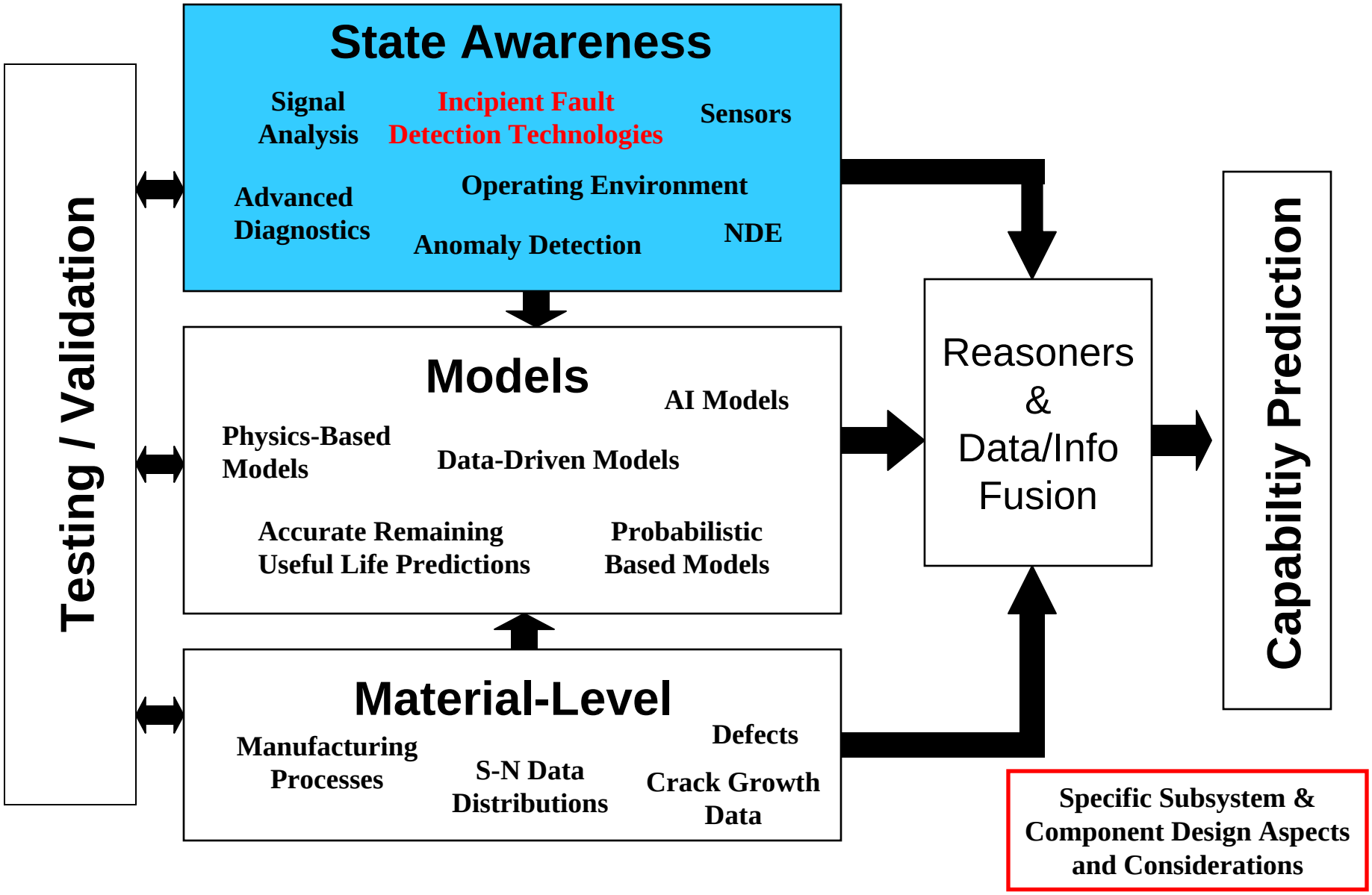
- **Better Understanding of Physics of Failure**
- **Condition Based Performance Predictions**
- **Better State Awareness Techniques**
  - **Advanced Sensors**
  - **Non-Traditional Detection**
  - **Smart Materials**
  - **Embedded Sensors and Detectable Materials**
- **Better Understanding of Incipient Crack Growth**
- **Better Understanding of Fault/Failure Progression Rates**
- **Better Understanding of Material Properties Under Different Loading Conditions and Mission Usage**
- **More Capable and Integrated Models: Physics, Statistical, Detector, Fleet Mission and Actual Usage based, etc.**
- **Better Data Fusion Methods**
- **Better Knowledge of Effects of Failures Across the Air Vehicle**
- **Study to Determine What Components to Perform Prognostics On**
- **Impacts of Changing Mission Mixes in Actual Fleet Usage**
- **A Comprehensive "Way Forward" Strategy, More Detailed Planning, and "Funded Support" Programs**

Notional

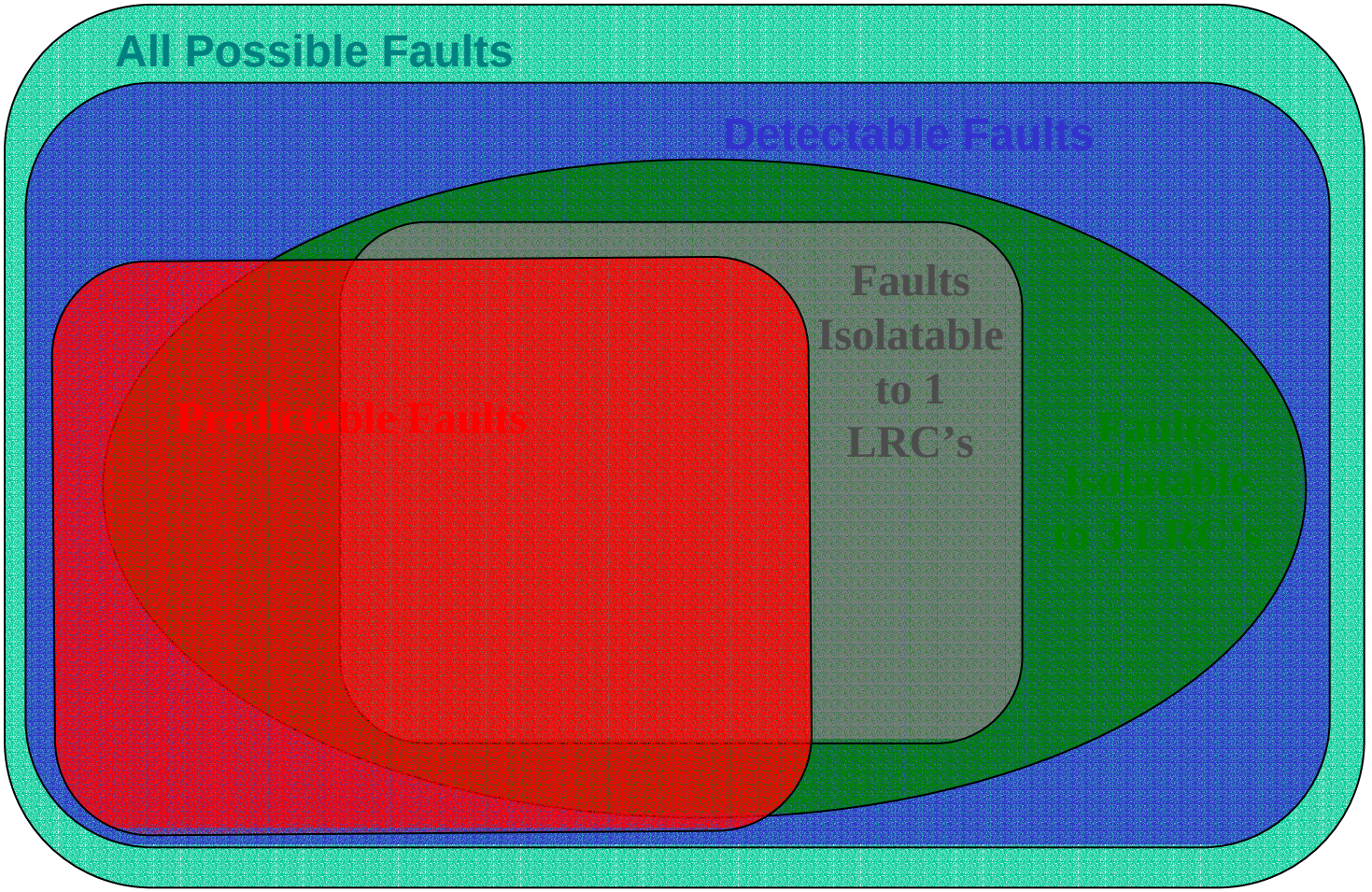
Roadmap to Predictive Prognostics



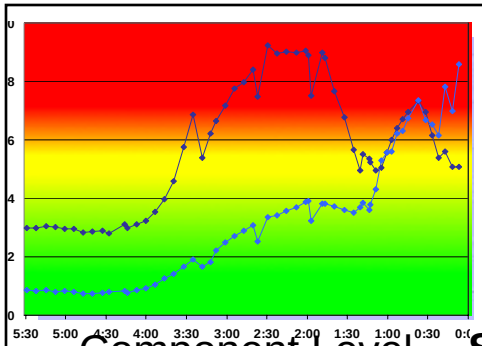
Predictive Prognostics - Integration Tasks



Detection/Isolation Analysis Update



H-60 IGB S-B Gear Fatigue Prognostics Module



Component Level Features

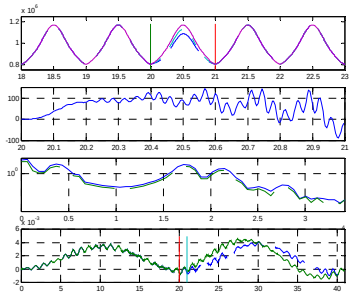
Raw Data

↓

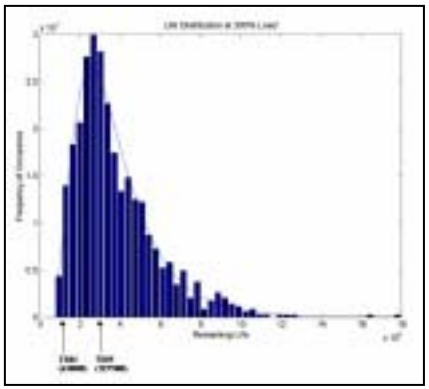
Features

↓

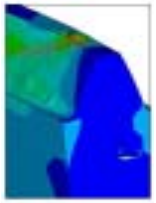
State Awareness

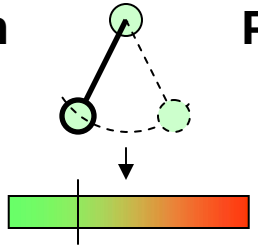


System Level Features

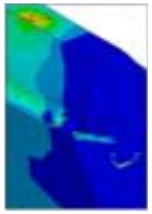


Initiation





Propagation



Material/Physics Stochastic Models

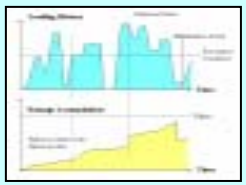
Probabilistic Fusion Process

Current/Future Capability Prediction

Will it last the mission?

What Operational changes must take place?

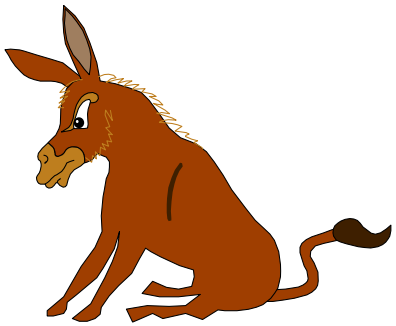
Interrogation Information



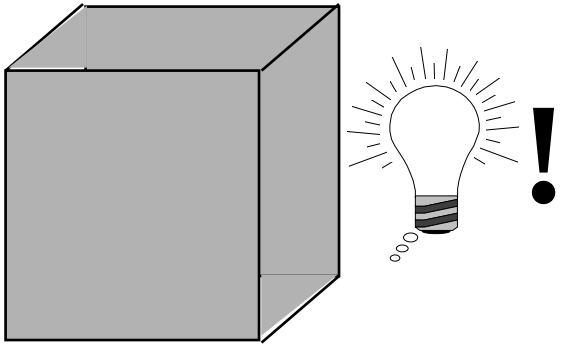
Expected Operating Conditions

Material Resume

The Question is:Why Not Prognostics and Health Management?



People resist change.



Protect rice bowls

Limited vision.

Problem is not **ONLY** in the capabilities, technologies and expected benefits; but in having the wrong people in the right positions, making the wrong decisions

Summary

- **The Needs Are Apparent**
- **Technology is Now NOT the Limiting Factor**
  - **And It will Only Improve With Time**
  - **There are Still a "Holes" to Fill in the Prognostics Base**
- **There are Enough Success Stories and Documentation that Justify Prognostics is Worth Pursuing**
- **All Elements are Coming Together To Enable Our Visions of Prognostics and Real Health Management**
- **We Must Implement and Apply Smartly and Wisely to Obtain Maximum Benefit**
- **Prognostics Not Just a Dream, Can Be Reality with Properly Directed Efforts**
- **Fill 'holes" in the Technology Base and Expand "Tool Kit"**

The Aggressive Application of On-Board, Real Time Prognostics is Within Reach, We Just Need the Proper Resources and Focus to Obtain It

DARPA PROGNOSTICS ROAD MAP



Space

- Engine Bearings
- Structures
- Tanking Materials
- Gimbals

Aviation

- JSF
  - Propulsion
  - Structures
  - LO
  - All Subsystems
- UCAVS & UAV



Ships

- AAAV
  - Bearing
  - Plumps

Ground

- Bearing
- Structures

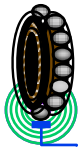

Seedling Projects

- Helo Gear Crack

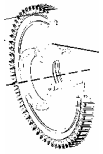
Feasibility Demo Phase 1

Prognostic Program Phase 2

- Engine Disk Crack
- Integrate Models
- Detection Sensors



- Continued Engine Disk and Blisk Crack Targeted for Modern Transition Application
- Global Integrated Models
- Composite Materials
- Engine Turbine Lite
- Bearings
- Structures




- State Awareness Technologies
  - Non-Traditional Focused Detection
  - Advance Sensors
  - Embedded Sensors and Detection
  - Smart Materials
  - Pattern Recognition

DARPA Seedling and Phase 1 Feasibility Demo Anticipated Accomplishments

- Identify and Target Components and Sub-elements Suitable for Prognostics
  - Those with understandable fault to failure progression characteristics
  - Eliminate those impossible or too hard to consider

- Prove Feasibility and Tractability
- Flush out and Define Successful and non Successful Technologies, Techniques, Methodologies, Approaches (areas)
- Document Lessons Learned

- Perform Experimental Seeded Fault Tests
  - As many as affordable
  - Designed for Specifically the Development of Prognostic Capabilities
- Define Most Workable Way Forward
- Demo and Refine an Approach Process Template that May be Used for any or many Types of Subsystem components
- Identify Needs and “Holes” in the Technology Base